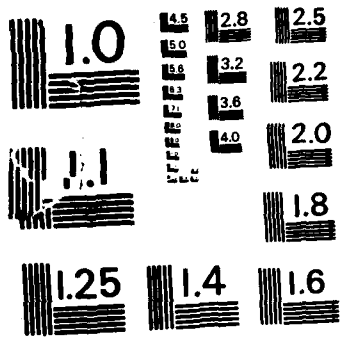
AD-A167 554 LASER VELOCIMETER MEASUREMENTS AND ANALYSIS IN TURBULENT FLOWS WITH COMBU..(U) PURDUE UNIV LAFAYETTE IN SCHOOL OF MECHANICAL ENGINEERING 1/1

UNCLASSIFIED H D THOMPSON ET AL. MAR 86 F/G 20/4 NL


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0

(2)

AD-A167 554

AFWAL-TR-82-2076
Part IV

LASER VELOCIMETER MEASUREMENTS AND ANALYSIS IN TURBULENT FLOWS WITH COMBUSTION

Part IV - Two-Component Cold-Flow Measurements

H. D. THOMPSON
W. H. STEVENSON
R. D. GOULD

SCHOOL OF MECHANICAL ENGINEERING
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA 47907

March 1986

Final Report for Period January 1981 - October 1984

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERNAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6563

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

ROGER R. CRAIG
Project Engineer

FRANK D. STULL, Chief
Ramjet Technology Branch
Advanced Propulsion Division
Aero Propulsion Laboratory

FOR THE COMMANDER

WILLIAM G. BEECROFT
Deputy Director, Advanced Propulsion Division
Aero Propulsion Laboratory

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/PORT*, W-PAFB, OH 45433 to help us maintain a current mailing list".*

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFWAL-TR-82-2076 Part IV	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): LASER VELOCIMETER MEASUREMENTS AND ANALYSIS IN TURBULENT FLOWS WITH COMBUSTION Part IV - TWO-COMPONENT COLD-FLOW MEASUREMENTS	5. TYPE OF REPORT & PERIOD COVERED: Final Report for Period Jan 81 - Oct 84
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): H. D. Thompson, W. H. Stevenson and R. D. Gould	8. CONTRACT OR GRANT NUMBER(s): F33615-81-K-2003
9. PERFORMING ORGANIZATION NAME AND ADDRESS: School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 2308 S1 07
11. CONTROLLING OFFICE NAME AND ADDRESS: Aero Propulsion Laboratory (AFWAL/PORT), Air Force Wright Aeronautical Lab. (AFSC), Wright-Patterson Air Force Base, Ohio 45433-6563	12. REPORT DATE: March 1986
	13. NUMBER OF PAGES: 36
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbulence measurements;
Laser velocimeter;
Bias errors; ~~(in laser velocimetry)~~
Recirculating flows.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A unique two-component, two color Laser Doppler Velocimeter (LDV) has been designed and built. The system includes Bragg cell modulators in all four beams, and a correction lens system to correct for the aberration induced by the cylindrical quartz test section. A dedicated PDP 11/40 mini-computer with DMA capability is used for data collection, storage, and processing. Two component (axial and radial) velocity measurements have been made in the turbulent flow field following an axisymmetric sudden expansion. Mean

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

streamwise and radial velocity and turbulence intensity measurements were made. Reynolds stresses were computed. The work previously reported in Parts I, II, and III of this report is briefly reviewed.

FOREWORD

This final technical report was submitted by the School of Mechanical Engineering of Purdue University under Contract No. F33615-81-K-2003 and covers the period 1 January 1981 - 2 October 1984. The research was sponsored by the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio, under Project No. 2308 with Dr. Roger R. Craig AFWAL/PORT as Project Engineer. Warren H. Stevenson and H. Doyle Thompson of Purdue University were technically responsible for the work.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

This is the final report on Air Force Contract No. F33615-81-K-2003, Project No. 2308 for the experimental and analytical study entitled, "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion." References 1 thru 13 are a direct result of the research. Additional work on the design, construction and preliminary measurements from a two component LDV system are reported in Section III of this report. The research is an extension of a previous Air Force contract, No. F33615-77-C-2010, Project No. 2308.

The major results of this research are briefly summarized in Section II.

SECTION II

SUMMARY OF MAJOR RESULTS

1. STUDENT SUPPORT AND THESES:

Three MSME theses were completed with support from this contract. They are listed here and as References 1-3.

1. Luchik, Thomas Stephen, "A Laser Velocimeter Investigation of Turbulent Flow in an Axisymmetric Sudden Expansion," MSME Thesis, Purdue University, May 1982.

2. Gould, R.D., "Laser Velocimeter Measurements in an Axisymmetric Sudden Expansion With and Without Combustion," MSME Thesis, Purdue University, May 1983.

3. Durrett, Russell P., "Laser Velocimeter Measurements in an Axisymmetric Sudden Expansion with a Correction for Tube Wall Aberrations," MSME Thesis, Purdue University, May 1984.

In addition, the Ph.D. work of R.D. Gould, now in progress, was partially supported from this contract.

2. REPORTS AND PUBLICATIONS

In addition to the three MSME theses listed above the following ten reports and publications are a direct result of the contract. References 4, 5 and 6 are the interim annual reports for the contract and References 7 thru 13 are conference papers and journal articles that have resulted from the research work.

4. Stevenson, W.H., Thompson, H.D. and Luchik, T.S., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part 1, September 1982.

5. Stevenson, W.H., Thompson, H.D. and Gould, R.D., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part II, July 1983.

6. Thompson, H.D., Stevenson, W.H. and Durrett, R.P., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion, Part III - A Correction Lens for Laser Doppler Measurements in a Cylindrical Tube," AFWAL-TR-82-2076, Part III, July 1984.

7. Stevenson, W.H., Thompson, H.D., Gould, R.D. and Craig, R.R., "Laser Velocimeter Measurements in Separated Flow with Combustion," Proceedings of the International Symposium on Applications of Laser Doppler Anemometry to Fluid Mechanics, Lisbon, Portugal, July 5-7 (1982). Also published in <u>Laser Anemometry in Fluid Mechanics</u>, LADOAN, Lisbon 1984 (eds. R. Adrian, D. Durao, F. Durst, H. Mishina and J. Whitelaw).

8. Stevenson, W.H., Thompson, H.D. and Craig, R.R., "Laser Velocimeter Measurements in Highly Turbulent Recirculating Flows," <u>Proceedings of the Symposium on Engineering Applications of Laser Velocimetry</u>, pp. 163-170, ASME Winter Annual Meeting, Phoenix, AZ, November 1982.

9. Gould, R.D., Stevenson, W.H. and Thompson, H.D., "Laser

Velocimeter Measurements in a Dump Combustor," ASME Paper 83-HT-47 National Heat Transfer Conference, Seattle, WA, July 1983.

10. Durrett, R.P., Gould, R.D., Stevenson, W.H. and Thompson, H.D., "A Correction Lens for Laser Doppler Velocimeter Measurements in a Cylindrical Tube," AIAA Paper No. 84-0429, 1984.

11. Stevenson, W.H., Thompson, H.D. and Craig, R.R., "Laser Velocimeter Measurements in Highly Turbulent Recirculating Flows," Journal of Fluids Engineering 106, pp. 173-180 (1984).

12. Durrett, R.P., Gould, R.D., Stevenson, W.H. and Thompson, H.D., "A Correction Lens for Laser Doppler Velocimeter Measurements in a Circular Tube," AIAA Journal 23, pp. 1387-1391 (1985).

13. Durrett, R.P., Stevenson, W.H. and Thompson, H.D., "Radial and Axial Turbulent Flow Measurements with an LDV in an Axisymmetric Sudden Expansion Air Flow," to be published, ASME Winter Annual Meeting, Nov. 17-22, 1985.

3. MAJOR ACCOMPLISHMENTS

The objective of this research has been to provide an increased understanding of the turbulent flow field in a dump combustor. The program has been primarily experimental, with some analytical modeling and comparison. It is an extension of

previous work documented in References 14 thru 24. The following have been accomplished:

1. A survey and analysis of the related literature. See References 1 thru 13.

2. The identification of bias errors that arise in LDV measurements and the development of measurement techniques to eliminate those bias errors. See References 17, 20 and 23. The identification of and elimination of bias errors has been a matter of continuing concern throughout both this and the previous research contracts. Major advances have been made. There remain some experimental situations for which it is neither possible to apply the bias elimination procedures that have been developed, nor to accurately compensate for bias errors in the data. Further work should be done in this area.

3. The development of a unique single-component LDV system, with variable beam angle and dual Bragg cell frequency shifters. The system could be rotated around the beam axis, permitting independent velocity component measurements at any desired angle in the plane perpendicular to the laser beam axis. See References 1 and 4.

4. The systematic determination of $\overline{U}$, $\overline{U}_\Phi$, $\overline{u'^2}$, $\overline{u_\Phi'^2}$ and $\overline{u'u_\Phi'}$ in an axisymmetric sudden expansion. Measurements were made throughout the recirculation region, the reattachment region, and in the recovery region. Logan's method (Ref.

25) was used to extract the desired velocity, turbulence and shear stress values from the individual measurements. Measured results were compared to computations. See Reference 1 and 4.

5. Measurements of $\overline{U}$ and $\overline{U'^2}$ in the recirculating and reattachment region of a combusting flow. The hot-flow results are compared to biased and unbiased cold-flow data and to computations. See References 2, 4, 7, and 9.

6. The modification of the CHAMPION/2/E/FIX Computer program to handle reacting flow with the step geometry used herein. The treatment of the boundary conditions required considerable modification. An extensive parametric study was conducted. This work was supported in part by NASA. See References 5 and 26.

7. The development of a correction lens system to correct for probe volume abberations caused by the circular tube wall. The correction lens prevents the probe volume from wandering when the LDV optics are rotated, and allows the LDV system to be used to traverse the flow field vertically. This in turn permits the measurement of the radial velocity component and also allows simultaneous radial and axial component measurements to be made with a 2-D LDV system. See References 3, 6, 10, and 12.

8. The compilation of benchmark cold-flow measurements just downstream of the sudden expansion, and in the recirculation

zone. The correction lens was used for these measurements and care was taken to eliminate bias errors. Measurements were made to determine $\overline{U}$, $\overline{U}_r$, $\overline{u'^2}$, $\overline{u_r'^2}$ and $\overline{u'u_r'}$. See Reference 13.

9. The development, design, and construction of a two-component LDV system with improved data recording and storage capabilities. Limited preliminary measurements in a cold-flow rig have been made. The system design and preliminary data are described in Section III of this report.

Section III

THE TWO COMPONENT SYSTEM

This section describes the two-component LDV system and presents some preliminary experimental data obtained in a cold-flow sudden expansion geometry.

1. THE LDV SYSTEM

A two-color, two-component LDV system operating in forward scatter has been developed. The initial application is simultaneous measurements of the axial and radial velocity components in an axisymmetric sudden expansion flow with and without combustion. The LDV system includes Bragg cell modulators in the four beam paths of the argon-ion laser to allow a net frequency shift of 5 MHz in both the green and blue beams. This permits an unambiguous measurement of negative velocities and also eliminates incomplete signal bias. The green beam optical probe volume has a waist diameter of 0.200 mm and is approximately 2 mm long. The blue beam has a probe volume waist of 0.250 mm and is approximately 1 mm long. The scattered light from the probe volume is separated using a dichroic filter so that approximately 80% of each color passes to its respective photomultiplier tube. Narrow bandpass filters are used to further filter unwanted signals before they are detected. A schematic diagram of the LDV system is shown in Figure 1.

The flow without combustion is seeded with oil particles (DOP) approximately 1 μm in diameter generated from a liquid

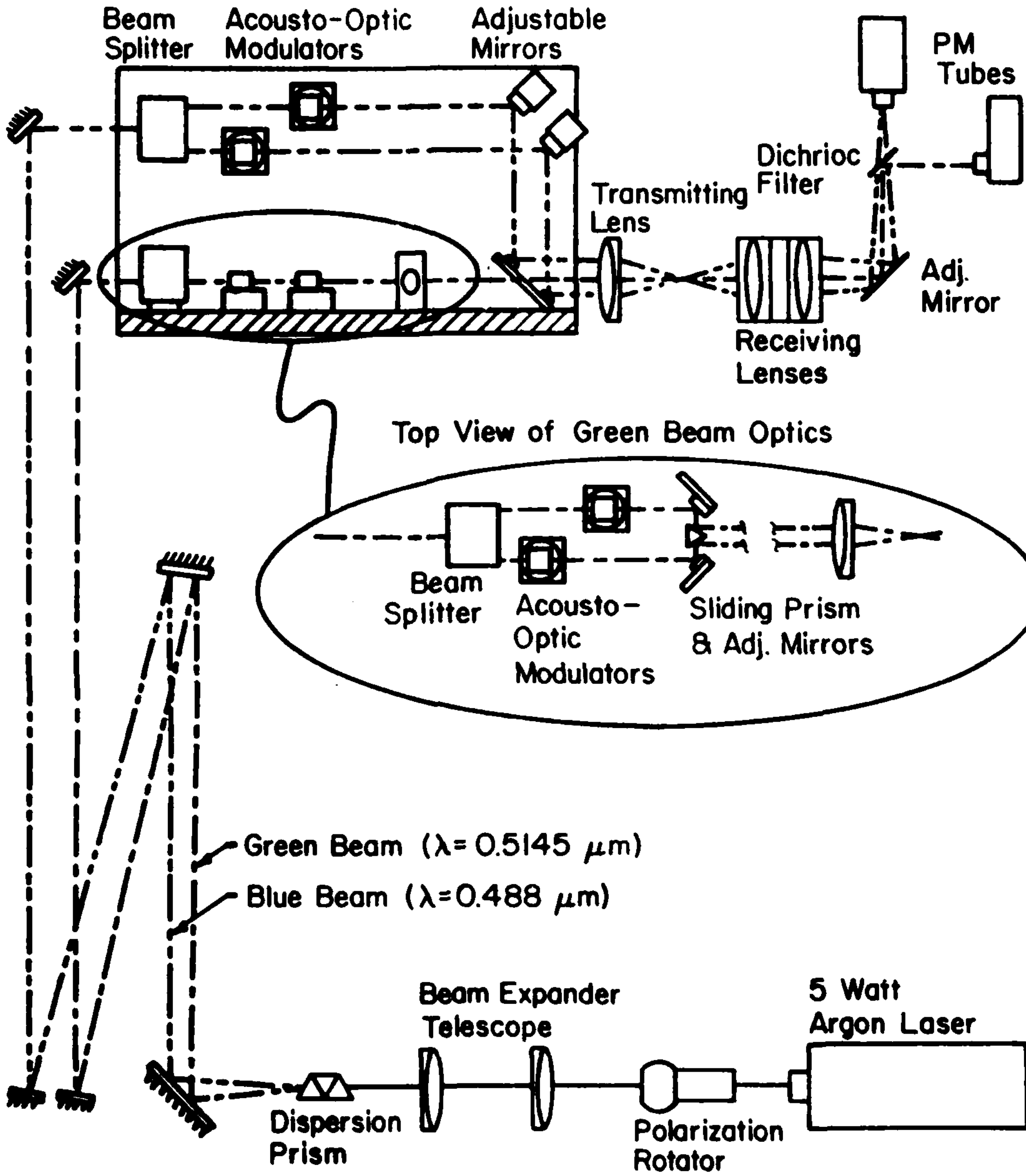


Figure 1. Two-Component LDV System.

atomizer followed by an evaporization-condensation unit. The flow with combustion will be seeded with 1 μm diameter aluminum oxide particles generated from a TSI model 3400 fluidized bed generator or from a home-built cyclone- type seeder, depending upon which seeder gives the best results. No testing has been performed using aluminum oxide seed particles to date. From some preliminary testing using this LDV system (with seed particles generated from the liquid atomizer) maximum data validation rates were found to be approximately 15,000 and 5,000 samples per second for the green (axial) and blue (radial) components, respectively. >From preliminary tests, it appears that maximum "coincident" data ready rates range between 1000 and 2000 per second. For this case, biased velocity data results as will be shown later.

In an effort to obtain accurate unbiased velocity data two approaches will be investigated. The first approach will involve minor LDV system modifications with the goal of improving the blue beam signal quality and therefore increasing the blue beam data validation rate to > 10,000 samples per second. If this can be accomplished the experimental technique for eliminating velocity bias by inhibiting the counter processors for a fixed time interval between samples, approximating equal time sampling, will be used [8,9,20,24,27,28].

If the signal quality of the blue beam cannot be improved, an attempt will be made to develop a velocity bias correction scheme. The second approach involves validating two proposed

velocity bias correction schemes. The two correction schemes of interest are the McLaughlin-Tiederman 2-D weighting correction [29,30] and the Barnett and Bentley time between data correction [31]. The two-component "corrected" data will then be compared to independent unbiased one-component data obtained using the interval sampling technique to validate and modify each correction scheme.

The data collection and processing system consists of two TSI model 1990 counter-type processors (one for each channel), a TSI model 1998 interface with coincidence timing electronics and a PDP 11/40 mini-computer with DMA capability. A digitized thermocouple signal will also be interfaced through the TSI 1998 interface so that coincident velocity-temperature data can be obtained (Figure 2). With this system it is possible to acquire velocity data from individual doppler burst signals at rates up to 50,000 samples per second (limited by seed density). The mini-computer and counter processors are also interfaced so that sampling can be controlled. This is accomplished with a hardware clock controlling the data-inhibit handshaking signals. The software developed for this experiment is capable of burst (measurement sampled and stored as soon as it is validated) or interval sampling. It can also access the extended memory in the PDP 11/40 allowing up to 96K words of data to be stored for each sample.

The data reduction program calculates three types of statistics for each sample. These include the standard statistic, the

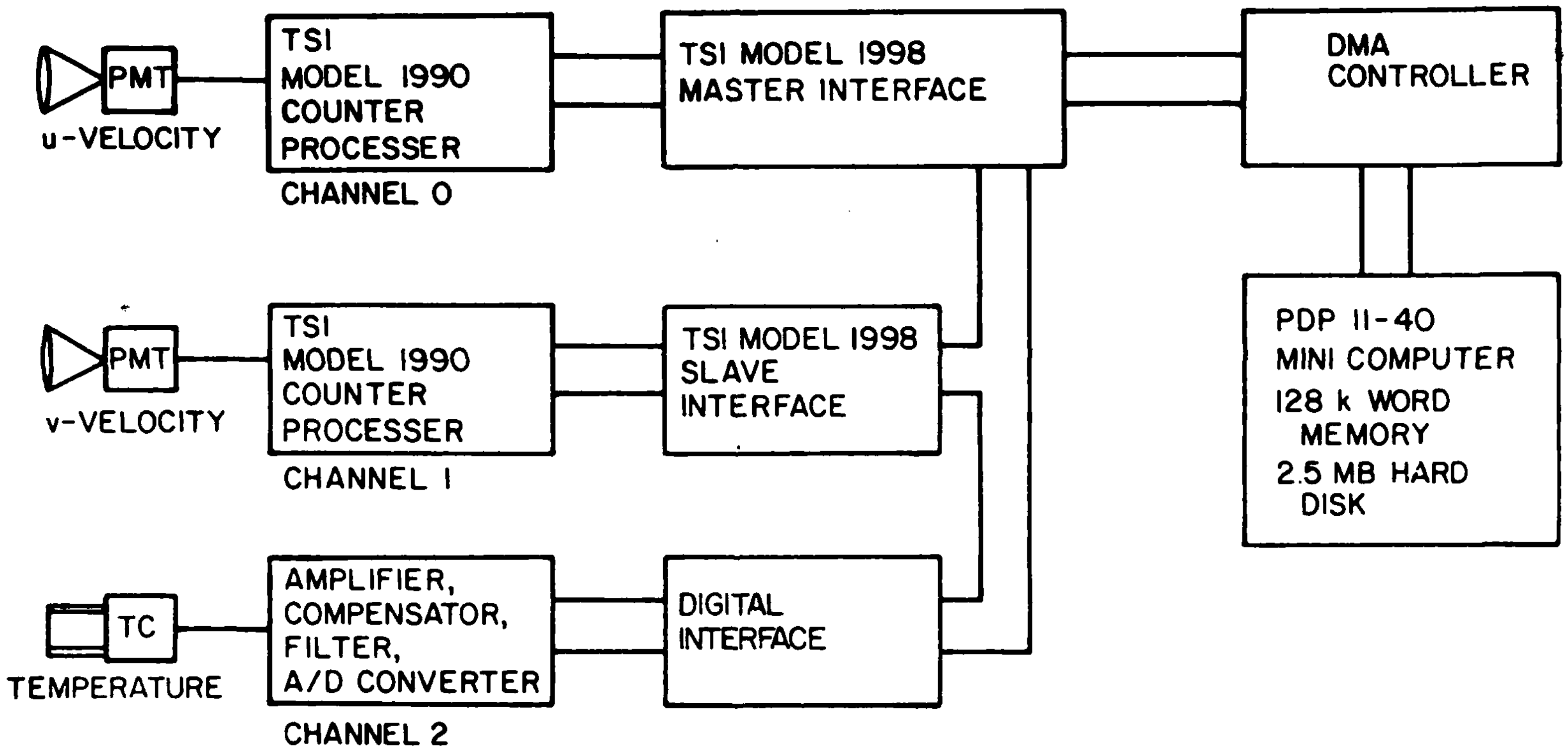


Figure 2. Data Acquisition System.

McLaughlin-Tiederman 2-D weighted statistic and the time between data weighted statistic. Data points lying outside $\pm 3\ \sigma$ (selectable) are discarded and revised statistics are calculated. Histograms are constructed for both velocity components on the terminal and can be routed to the line printer for hard copies. The data can also be stored on the hard disk.

2. THE TEST RIG

The flow system utilized in this experiment is illustrated in Figure 3. Air is provided by a radial fan blower followed by a flow conditioning section consisting of honeycomb flow straighteners. Fuel (gaseous propane) will be injected in the duct immediately following the blower through a multi-port manifold to give a homogeneous fuel-air mixture. The test section consists of a converging inlet nozzle with an exit diameter of 76.2 mm followed by a 152.4 mm diameter downstream section. This inlet was chosen to give a uniform inlet velocity profile. The static pressure drop across the nozzle is used to monitor the inlet flow condition. The test section was extruded from optical quality fused quartz and allows measurements throughout the flowfield for x/h values ranging from 0.3 to 14. The test section design is shown in Figure 4.

3. CORRECTION LENS

A correction lens to allow simultaneous axial and radial velocity measurements in a cylindrical tube has been designed and fabricated using the procedure described in Reference 12. The

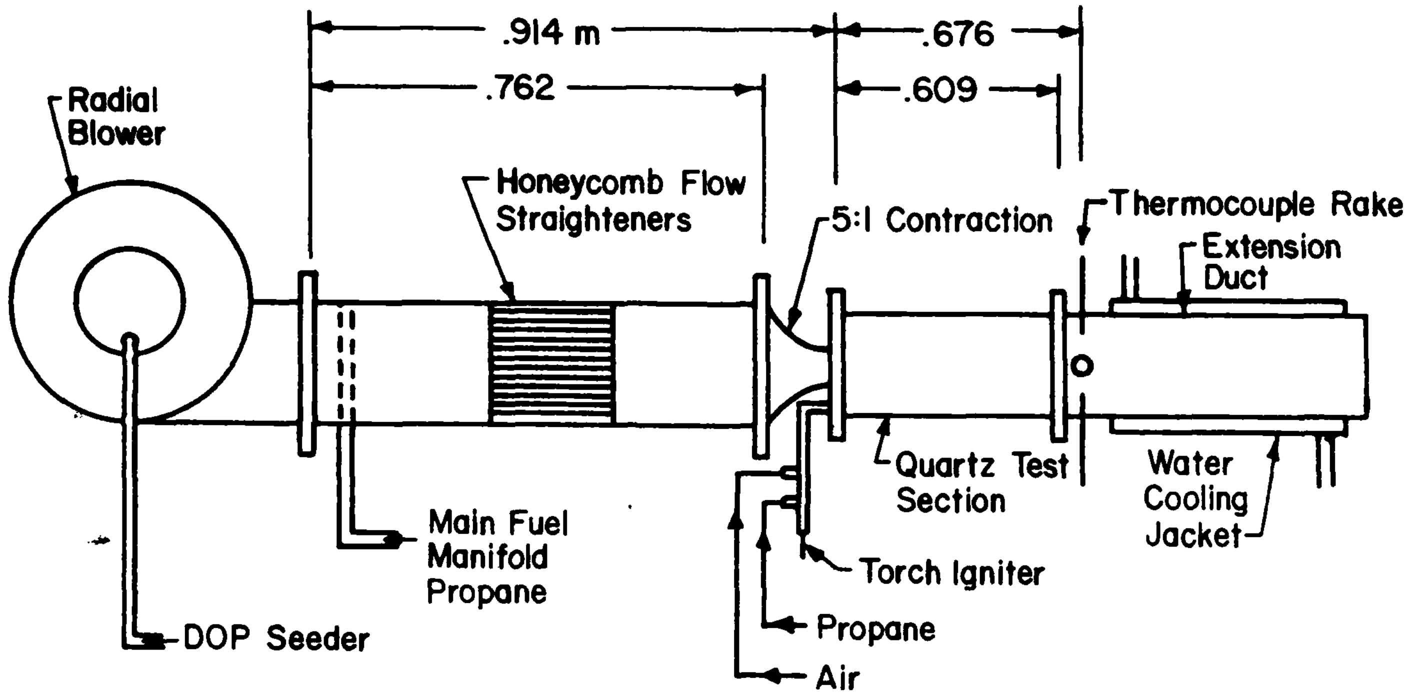


Figure 3. Flow System.

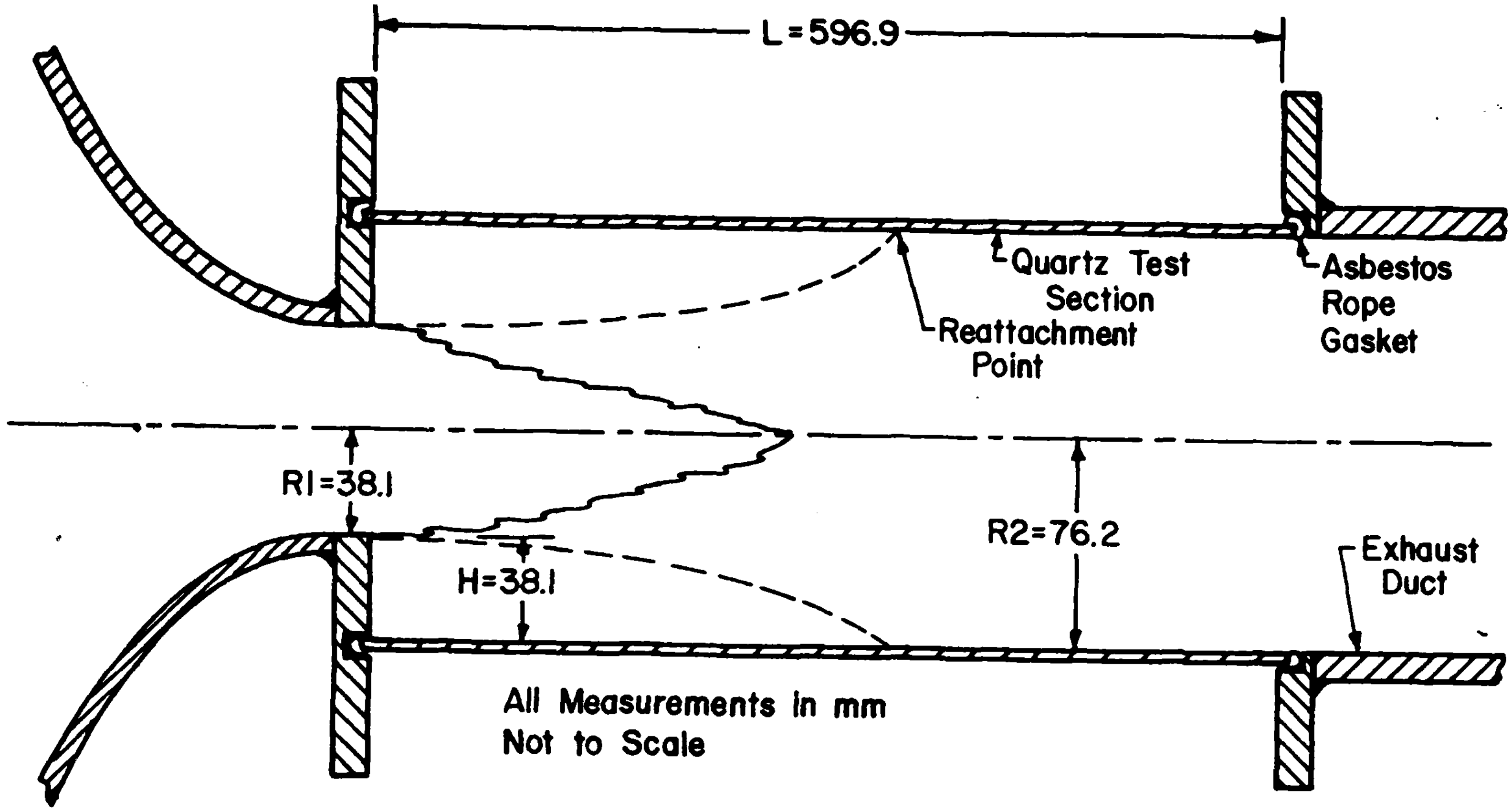


Figure 4. Test Section.

planar-concave cylindrical lens that corrects for the aberration induced by the quartz test section has a radius of curvature of 3.3528 m, a thickness at its center of 17.93 mm and a refractive index of 1.52. The correction lens insures that the orthogonal probe volumes (green and blue) intersect to within 100 μm along the length of the probe volume and to within 25 μm along the diameter of the probe volume. This forces the scattered light from the different colored probe volumes to come from approximately the same point. The correction lens system is comprised of two lenses, one on the transmitting side and one on the receiving side of the test section as shown in Figure 5. This is due to the symmetry of the system. The lenses have to be moved away from the test section as the measurement point moves further off axis. A ray tracing program is used to determine the placement of the lenses and also gives the real probe volume intersection relative to the beam intersection if no test section or lens was present. Simultaneous axial-radial velocity measurements can be made out to a non-dimensional radius of approximately 85% with this system.

4. PRELIMINARY EXPERIMENTAL DATA

A substantial amount of preliminary two dimensional data have been taken in an effort to validate the LDV system, the flow characteristics of the test rig, the correction lens performance and the data acquisition and reduction software. A free jet flow was used initially and later replaced by the more complicated axisymmetric sudden expansion flow. As mentioned earlier only

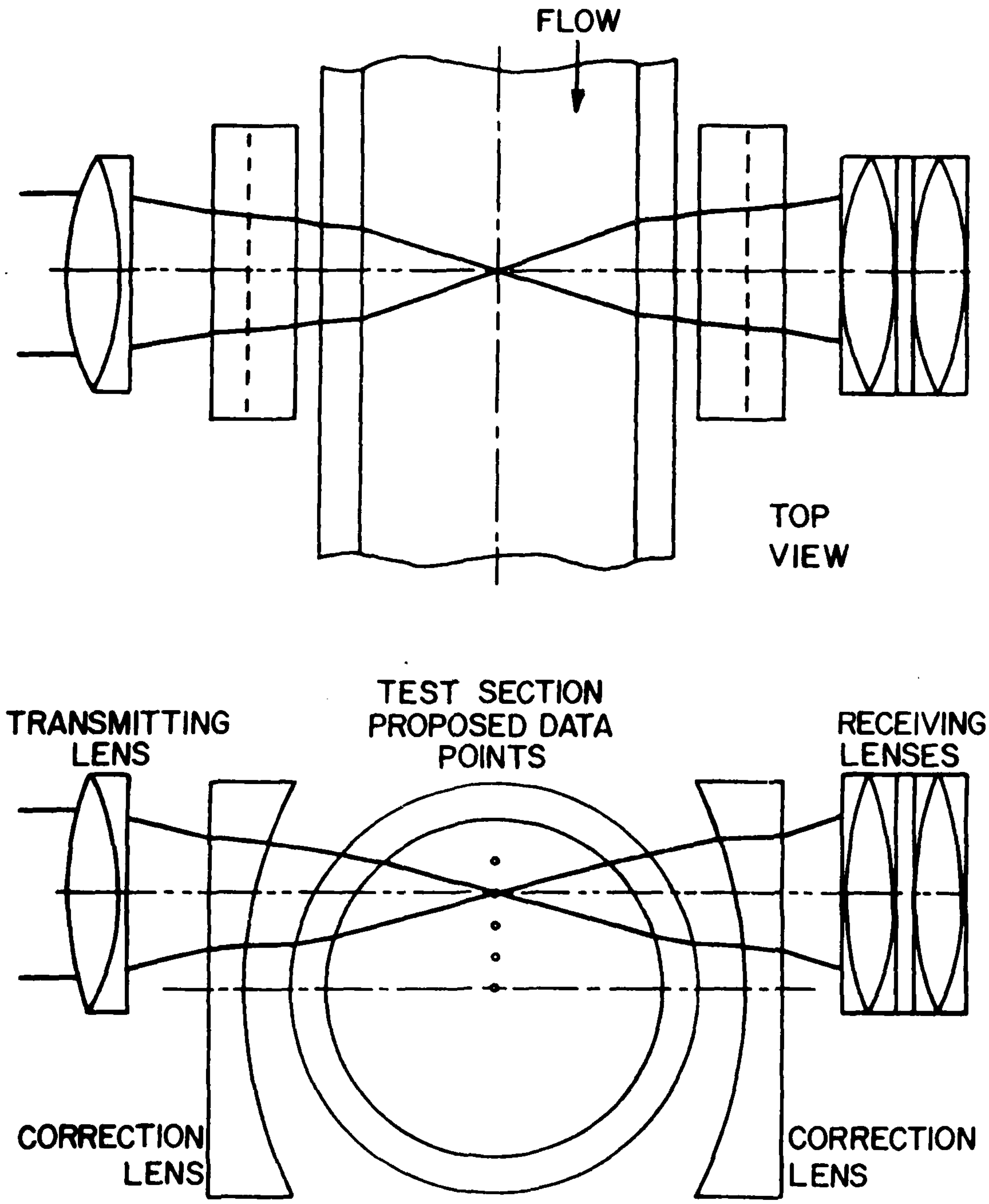


Figure 5. Correction Lens System.

non-reacting flow experiments have been run to date. The following data set was acquired using the 2-component LDV and data acquisition system described in the previous section.

The measurements were made in the axisymmetric sudden expansion flow (Figure 4) using the correction lens system. The inlet velocity was uniform with a value of 22 m/s corresponding to a Reynolds number of 5.5×10^4 based on step height. Seeding was provided by the liquid atomizer described earlier. The burst sampling technique was used to obtain all the data presented here. Because the data are biased, owing to the sampling method used, the McLaughlin-Tiederman 2-D correction is also applied. This preliminary data set consists of measurements across the radius of the test section at 4 non-dimensional axial locations, namely $x/H = 0.3, 2, 4$ and 6.

Figure 6 shows the mean axial velocities (corrected and uncorrected) at the four axial planes. Notice that the corrected data has lower values of mean velocity in the shear layer where turbulence is high and has approximately the same value as the uncorrected velocity in regions of low turbulence. This is the expected result. These preliminary measurements are presented only to demonstrate LDV system performance. They are known to suffer from inaccuracy as a direct result of (1) the slowly oscillating shear layer characteristic of this flow field and (2) the burst sampling technique. The first problem occurs because the data was gathered at a high rate. This means the entire sample ($n = 6000$) was collected in a very short time (typically < 2

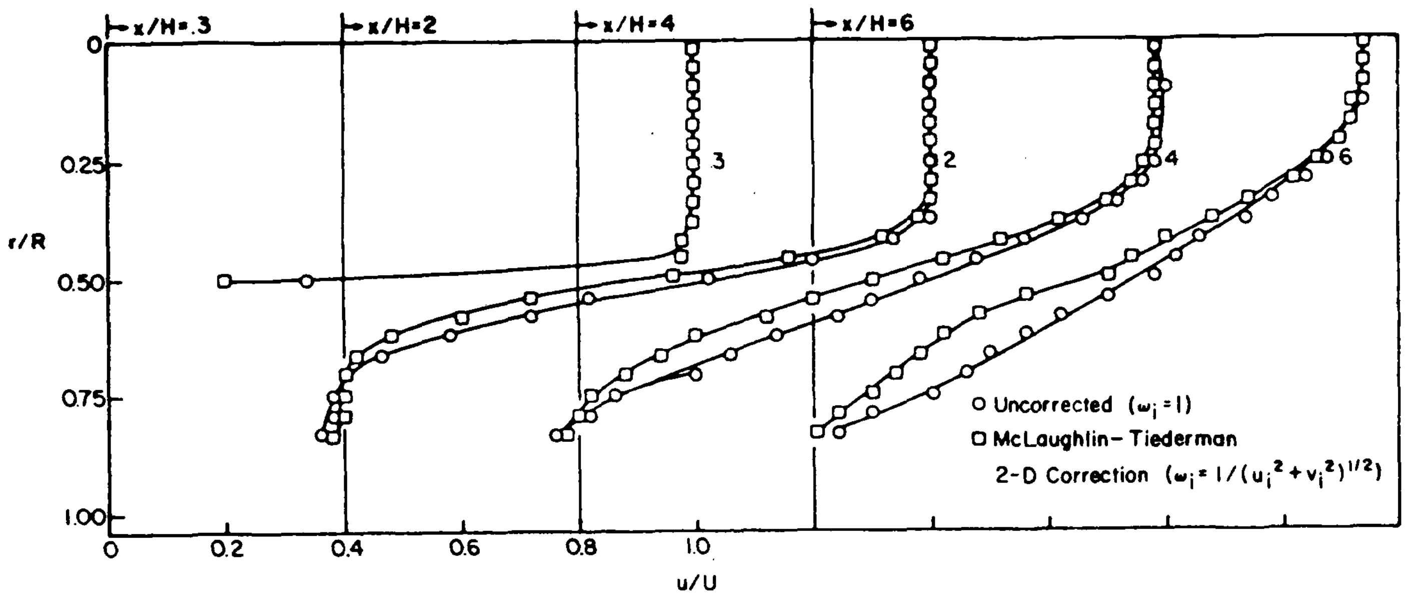


Figure 6. Normalized Axial Velocity

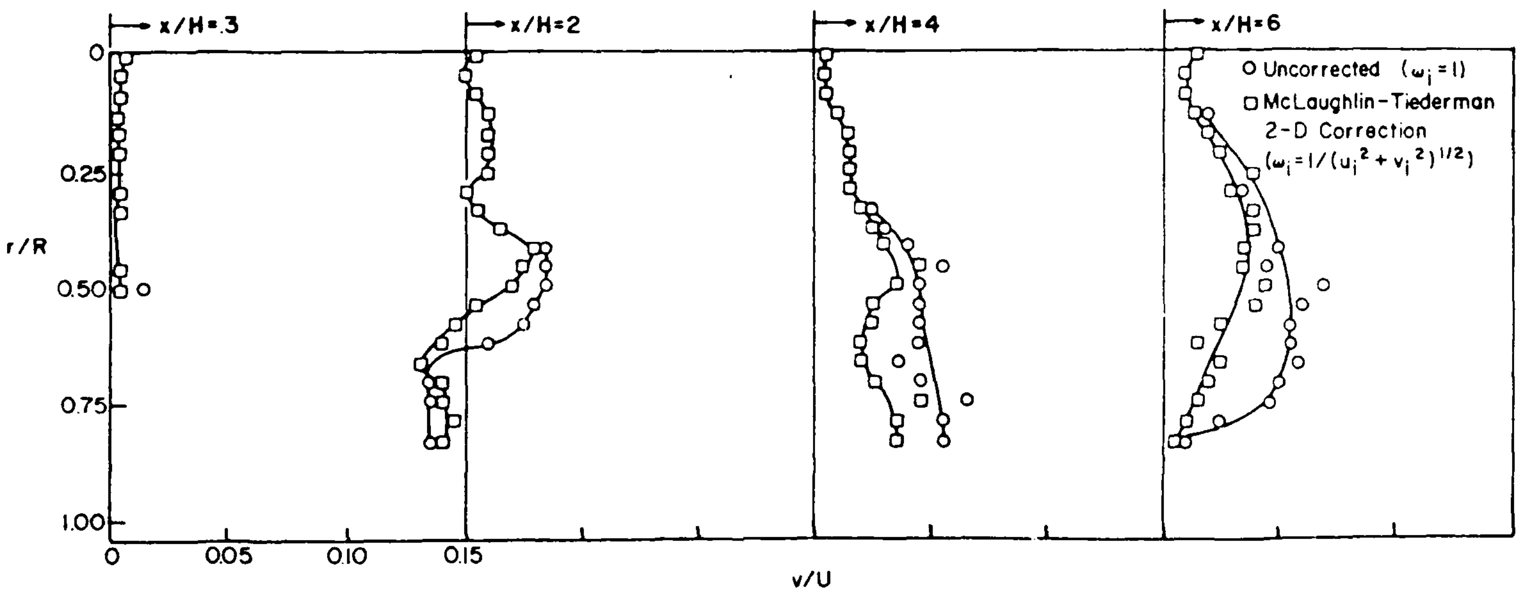


Figure 7. Normalized Radial Velocity

sec) and the statistical parameters of the sampled data depend on when in the low frequency cycle the data is collected. The observed variation in the mean axial velocity due to this unsteadiness was up to 10%. This "inaccuracy" is much greater than the statistical error due to the finite number of samples taken. Typically, in a well-defined experiment, mean velocities are repeatable to better than 1%. The second source of inaccuracy (the burst sampling technique) is a velocity bias problem. Although the 2-D bias correction was applied, it was found to over correct the results in regions of high turbulence. This was confirmed by comparing unbiased one-component (axial) data to the 2-D corrected data. More work has to be done to determine the errors involved due to velocity bias and over-correction.

Figure 7 shows the mean radial velocity component at the four axial planes. Not much can be said about the data except that the very low radial velocity in this flow field is responsible for more scatter. The low signal quality of the blue beam could also be responsible for some of this scatter.

Figures 8 and 9 show the axial and radial normalized turbulence intensities, respectively. The 2-D weighted data show the correct trends [9,27] relative to the uncorrected (biased) data and reach the same maximum values as other investigators have found [9,13]. Notice the shift in the locations of peak turbulence intensities depending on whether a standard or weighted statistic is used. These figures show the magnitude of error that can be caused by biased velocity measurements and

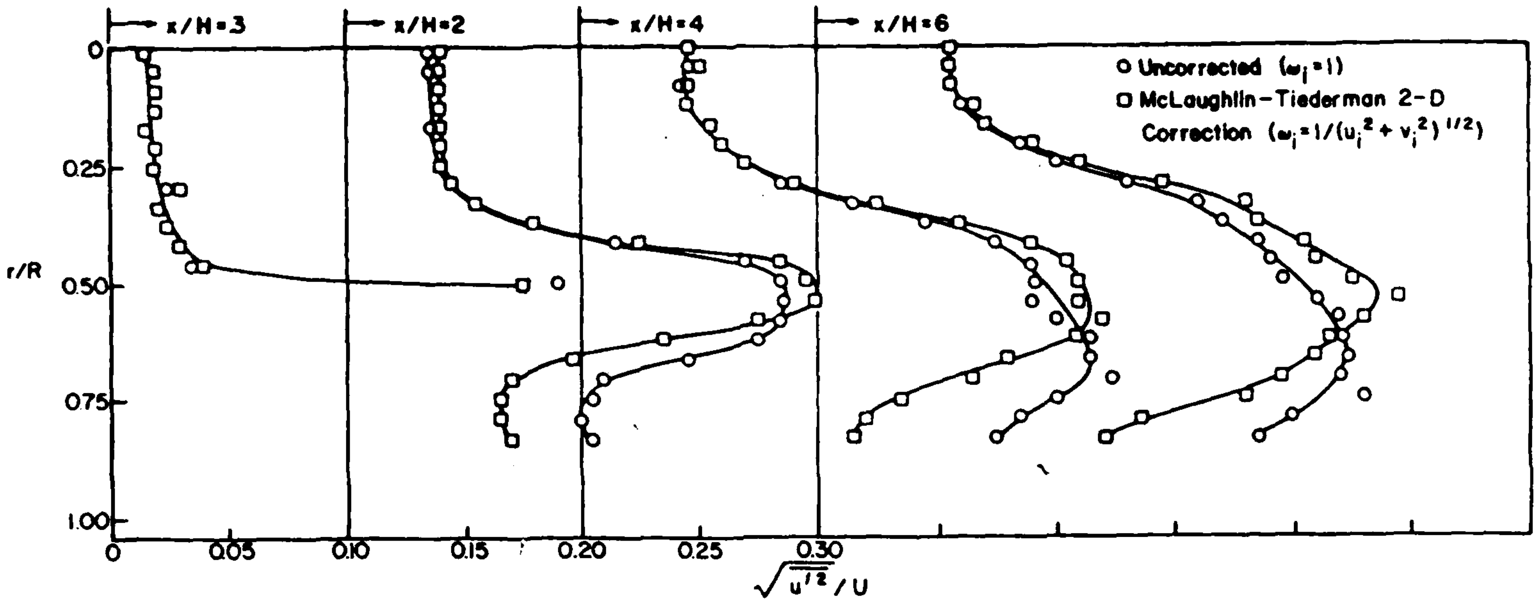


Figure 8. Normalized Axial Turbulence Intensity

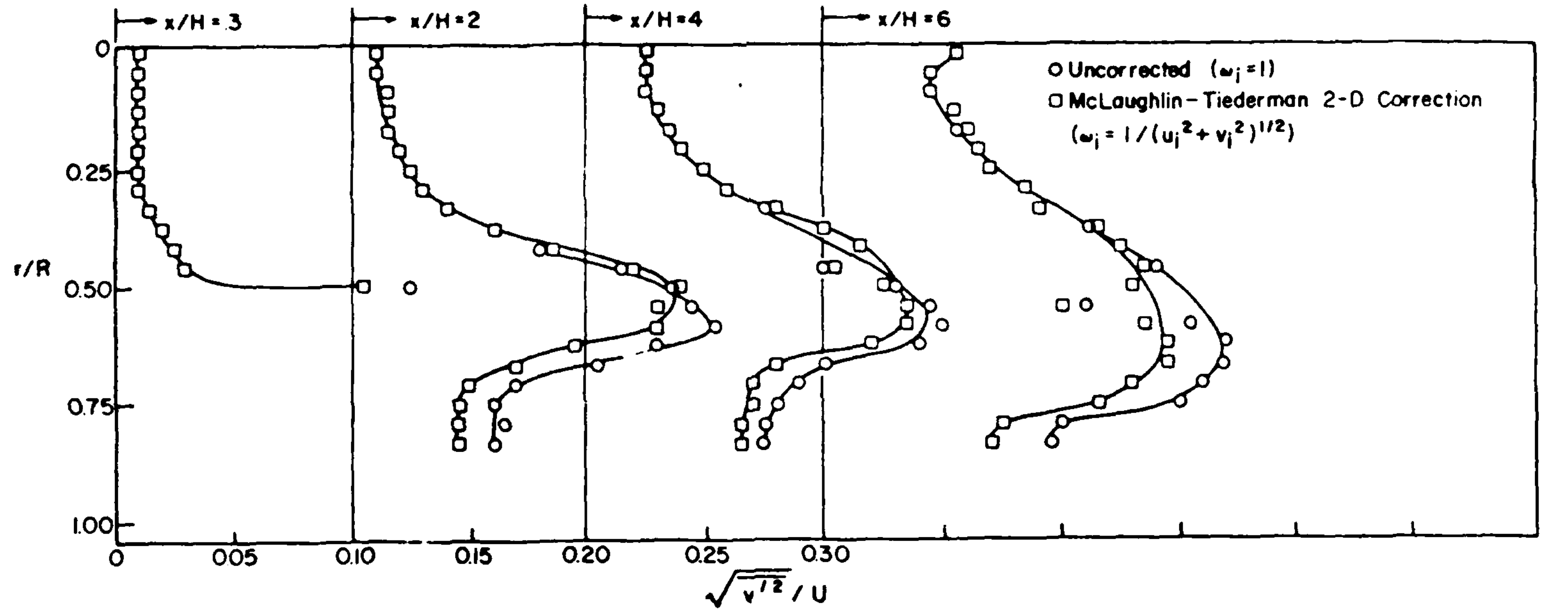


Figure 9. Normalized Radial Turbulence Intensity.

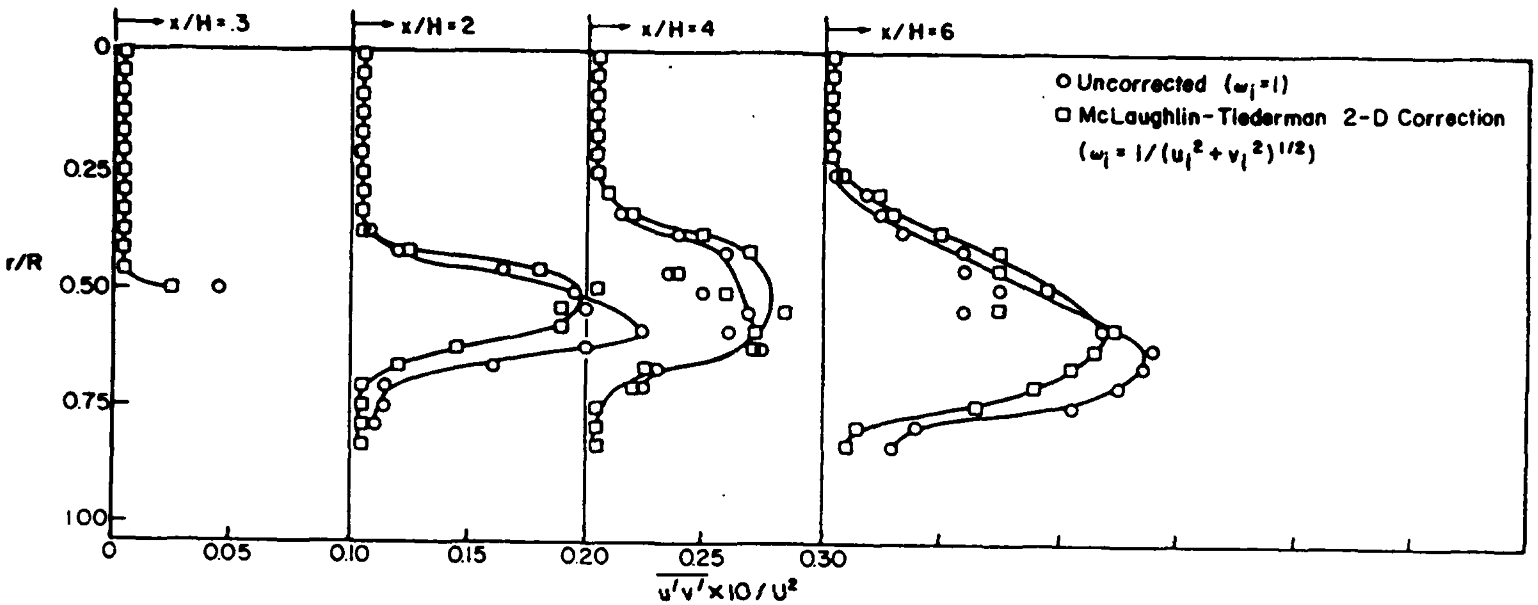


Figure 10. Normalized Reynolds Stress

illustrate that completely unbiased data are needed to improve existing time-averaged turbulence models.

Figure 10 shows simultaneous Reynold's stress measurements made with the coincidence window set to 10 μs (the minimum value on the TSI 1998 interface). Again, significant differences exist between the corrected and uncorrected statistic in regions of high turbulence. Also, more scatter is associated with this statistic, probably due to the low signal quality of the radial velocity component. However, the maximum values of normalized Reynold's stress agree well with other experimenter's values [13].

LIST OF REFERENCES

1. Luchik, Thomas Stephen, "A Laser Velocimeter Investigation of Turbulent Flow in an Axisymmetric Sudden Expansion," MSME Thesis, Purdue University, May 1982.

2. Gould, R.D., "Laser Velocimeter Measurements in an Axisymmetric Sudden Expansion With and Without Combustion," MSME thesis, Purdue University, May 1983.

3. Durrett, Russell P., "Laser Velocimeter Measurements in an Axisymmetric Sudden Expansion with a Correction for Tube Wall Aberrations," MSME Thesis, Purdue University, May 1984.

4. Stevenson, W.H., Thompson, H.D. and Luchik, T.S., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part 1, September 1982.

5. Stevenson, W.H., Thompson, H.D. and Gould, R.D., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion," AFWAL-TR-82-2076, Part II, July 1983.

6. Thompson, H.D., Stevenson, W.H. and Durrett, R.P., "Laser Velocimeter Measurements and Analysis in Turbulent Flows with Combustion, Part III - A Correction Lens for Laser Doppler Measurements in a Cylindrical Tube," AFWAL-TR-82-2076, Part III, July 1984.

7. Stevenson, W.H., Thompson, H.D., Gould, R.D. and Craig, R.R., "Laser Velocimeter Measurements in Separated Flow with

Combustion," Proceedings of the International Symposium on Applications of Laser Doppler Anemometry to Fluid Mechanics, Lisbon, Portugal, July 5-7 (1982). Also published in Laser Anemometry in Fluid Mechanics, LADOAN, Lisbon 1984 (eds. R. Adrian, D. Durao, F. Durst, H. Mishina and J. Whitelaw).

8. Stevenson, W.H., Thompson, H.D. and Craig, R.R., "Laser Velocimeter Measurements in Highly Turbulent Recirculating Flows," Proceedings of the Symposium on Engineering Applications of Laser Velocimetry, pp. 163-170, ASME Winter Annual Meeting, Phoenix, AZ, November 1982.

9. Gould, R.D., Stevenson, W.H. and Thompson, H.D., "Laser Velocimeter Measurements in a Dump Combustor," ASME Paper 83-HT-47 National Heat Transfer Conference, Seattle, WA, July 1983.

10. Durrett, R.P., Gould, R.D., Stevenson, W.H. and Thompson, H.D., "A Correction Lens for Laser Doppler Velocimeter Measurements in a Cylindrical Tube," AIAA Paper No. 84-0429, 1984.

11. Stevenson, W.H., Thompson, H.D. and Craig, R.R., "Laser Velocimeter Measurements in Highly Turbulent Recirculating Flows," Journal of Fluids Engineering 106, pp. 173-180 (1984).

12. Durrett, R.P., Gould, R.D., Stevenson, W.H. and Thompson, H.D., "A Correction Lens for Laser Doppler Velocimeter Meas-

urements in a Circular Tube," AIAA Journal 23, pp. 1387-1391 (1985).

13. Durrett, R.P., Stevenson, W.H. and Thompson, H.D., "Radial and Axial Turbulent Flow Measurements with an LDV in an Axisymmetric Sudden Expansion Air Flow," to be published, ASME Winter Annual Meeting, Nov. 17-22, 1985.

14. Stevenson, W.H., Thompson, H.D, "Laser Velocimeter Measurements in Turbulent and Mixing Flows," AFWAL-TR-79-2009, March 1979.

15. McVey, Ray, "The Design of a Laser Doppler Velocimeter for Use in Studying Turbulent and Mixing Flows." MSME Thesis, Purdue University, June 1979.

16. Stevenson, W.H. and Thompson, H.D., Bremmer, R. and Roesler, T. "Laser Velocimeter Measurements in Turbulent and Mixing Flows - Part II," AFAPL-TR-79-2009-Part II, March 1980.

17. Roesler, Timothy C., "Investigation of Bias Errors in Laser Doppler Velocimeter Measurements." Published as "Direct Measurement of LDA Bias Errors in Turbulent Flow." Symposium on Long Range and Short Range Optical Velocity Measurements. German-French Research Institute (ISL), Saint-Louis, France, Sept. 15-18, 1980, and "Measurements of Laser Velocimeter Bias Errors in Turbulent Flow," AIAA Journal, Vol. 20, No. 12, Dec. 1982, pp. 1720-1723. MSME Thesis, Purdue University, August 1980.

18. Bremmer, Robin John, "An Experimental and Numerical Comparison of Turbulent Flow Over a Step." MSME Thesis, Purdue University, August 1980.

19. Stevenson, W.H., Thompson, H.D. and Roesler, T., "Direct Measurement of LDA Bias Errors in Turbulent Flow," Symposium on Long Range and Short Range Optical Velocity Measurements, German-French Research Institute (ISL), Saint Louis, France, Sept. 15-18, 1980.

20. Roesler, T., Stevenson, W.H. and Thompson, H.D., "Investigation of Bias Errors in Laser Doppler Velocimeter Measurements," AFWAL-TR-80-2105, December 1980.

21. Bremmer, R., Thompson, H.D. and Stevenson, W.H., "An Experimental and Numerical Comparison of Turbulent Flow Over a Step," AFWAL-TR-80-2108, December 1980.

22. Stevenson, W.H., Thompson, H.D. and Luchik, T.S., "Laser Velocimeter Measurements in Turbulent and Mixing Flows - Part III," AFWAL-TR-2009-Part III, January 1981.

23. Stevenson, W.H., Thompson, H.D., Gould, R.D. and Craig, R.R., "Laser Velocimeter Measurements in Separated Flow with Combustion," Proceedings of the International Symposium on Applications of Laser-Doppler Anemometry to Fluid Mechanics, pp. 11.5.1-11.5.10, 5-7 July 1982, Losbon, Portugal.

24. Stevenson, W.H., Thompson, H.D. and Roesler, T.C., "Direct Measurement of Laser Velocimeter Bias Errors in a Turbulent

Flow," AIAA Journal, Vol. 20, pp. 1720-1723, December 1982.

25. Logan, S.E., "A Laser Velocimeter for Reynolds Stress and Other Turbulence Measurements," AIAA Journal, 10, 933 (1972).

26. Gould, R.D., Stevenson, W.H. and Thompson, H.D., "Turbulence Characteristics of an Axisymmetric Reacting Flow," NASA CP-2309, Combustion Fundamentals Research, pp. 189-198 (1984).

27. Johnson, D.A., Modarress, D. and Owen, F.K., "An Experimental Verification of Laser-Velocimeter Sampling Bias Correction," Proceedings of the Symposium on Engineering Application of Laser Velocimetry, ASME Winter Annual Meeting, Phoenix, AZ, November 1982.

28. Craig, R.R., Nejad, A.S., Hahn, E.Y. and Schwartzkopf, K.G., "A General Approach for Obtaining Unbiased LDV Data in Highly Turbulent Non-Reacting and Reacting Flows," AIAA-84-0366, Jan. 1984, AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada.

29. McLaughlin, D.K. and Tiederman, W.G., "Bias Correction for Individual Realization Laser Anemometry Measurements in Turbulent Flows," Physics of Fluids, Vol. 16, No. 12, p. 2082, 1973.

30. Tiederman, W.G., "Interpretation of Laser Velocimeter Measurements in Turbulent Boundary Layers and Regions of Separation," Fifth Biennial Symposium on Turbulence, University of

Missouri-Rolla, Edited by G.K. Patterson and J.L. Zakin, Science Press, pp. 153-161, 1977.

31. Barnett, D. and Bentley, H., "Statistical Bias of Individual Realization Laser Velocimeters," Proceedings of the Second International Workshop on Laser Velocimetry, Purdue University, p. 428, 1974.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1986 — 646-067/40779

END

DTIC

6-86